Journal of Cleaner Production 203 (2018) 708–717

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Scenario analysis of emissions structure under climate change in China

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ARTICLE INFO

Article history:
Received 30 March 2018
Received in revised form
26 July 2018
Accepted 4 August 2018
Available online 22 August 2018

Keywords:
Energy structure
Carbon emissions
Scenarios
Future development

ABSTRACT

This study calculated the CO_2 emissions due to fossil fuel consumption in China during 2000–2015 with consideration of the regional coal-, oil-, and gas-related variations. We used logarithmic mean Divisia index methods to establish the primary influencing factors of CO_2 emissions, and we extended the UK National Ecosystem Assessment Scenarios to forecast future CO_2 emissions related to fossil fuel use during 2020–2030. It was determined economic development is the main reason for increased CO_2 emissions, and that energy intensity and energy structure decreased CO_2 emissions. Finally, we considered six scenarios to predict the future development of coal, oil, and gas consumption in China. Six scenarios including Go with the Flow, Nature@work, Green and Pleasant Land, World Market, National Security and Local Stewardship, results show Green and Pleasant Land will induced coal and oil emission decrease and gas emission slightly increase. The results obtained based on analysis of CO_2 emissions and identification of regional influencing factors could provide useful information for decision makers regarding the allocation of fossil fuel use.

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1. Introduction

Global climate change is a problem with consequences that affect sustainable development for all humankind. The problem of climate change has been extended from a scientific issue to one of international concern (Wang et al., 2016). Climate change not only represents a huge environmental problem faced by humankind (IPCC, 2014a), but it is also a major factor affecting future global economic development (IPCC, 2014b), political structures, and international diplomatic relations (Adger et al., 2013). Global climate change is a critical problem that must be resolved by international cooperation through debate between developing and developed countries and among different developed countries on the mitigation of greenhouse gas emissions and the protection of the environment (UNFCCC, 2007).

Climate change will alter considerably the distribution pattern of climate resources, which will affect all aspects of human society. Specifically, it will affect the safety of agricultural production and it will represent a headwind to increasing crop yields (Davidson, 2016). As the temperature rises, pest-hit areas could expand, further increasing the costs of agricultural production (Scherr et al., 2012), thus the complex influence could be systemically in decision and control (Amini, 2018). In addition, climate change will cause many adverse effects for the energy industry, industrial production, transportation, services, and people's livelihoods (Chen et al., 2017). For example, an abnormal climate will adversely affect agriculture, forestry, husbandry, and fisheries, the effects of which will then spread to the downstream food manufacturing and processing industries (Gunawansa et al., 2014). Global climate change is closely related to energy generation and the associated unprecedented consumption of fossil fuels (Li et al., 2017), which have produced emissions of greenhouse gases that have exacerbated the “greenhouse effect” and accelerated the trend of global warming (Deng et al., 2017). Among the primary greenhouse gases known to cause climate change, CO_2 accounts for 75% (Schuur et al., 2015). Of the CO_2 emissions derived from anthropogenic activities, 70% are derived from the combustion of fossil fuels (Zhang et al., 2015) and 80% of those are attributable to solid fuels (Tahir et al., 2013). China,

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https://doi.org/10.1016/j.jclepro.2018.08.045
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as one of the world's largest producers and consumers of coal, and also as an emerging power undergoing rapid industrialization and urbanization, will continue to see its need for energy production increase in the coming years, which will result in increased CO_2 emissions (Yuan et al., 2018). Given the attention placed by the international community on the problem of climate change, campaigns to save energy and to reduce harmful emissions have become urgent in relation to China's current socioeconomic development (den Elzen et al., 2016).

From 1973 to 1998, the global energy supply increased by 57% (Iea, 2012), for which the consumptions of oil, natural gas, and coal were dominant, followed by nuclear power, hydropower, and other renewable energy sources (Moriarty and Honnery, 2012). In different regions of the world, the fuels consumed and the primary energy-consuming sectors are substantially different. For example, natural gas is the main energy source consumed in Russia (Boussena et al., 2013). Coal, natural gas, and other fossil fuels provide most of the energy used by the industrial sector of the U.S.A. (Medlock, 2012). China's energy consumption is focused mostly on coal (World Energy Council, 2013). In Malaysia, the transportation sector accounts for 40% of the total energy consumption (Ong et al., 2011). Many other developing countries such as Bangladesh still rely primarily on biomass energy (Huda et al., 2014), which also constitutes the main source of pollution of indoor air in developing countries.

During 1978–2015, China's gross domestic product (GDP) grew rapidly (Holz, 2014). China's economic development in previous years can be divided into two periods: slow growth during 1952–1977 and rapid growth from 1978 to 2016 (Fig. 1). During the earlier period, China's economy developed slowly and the large population base resulted in a reasonably low per capita GDP. During the latter period, i.e., since the reform and the opening up of China, the nation's economy has experienced high-speed growth, which has driven substantial advances in per capita GDP. In particular, since the period of the "Ninth Five-Year Plan," the growth of the national economy has shown an exponential upward trend.

The national economic structure of China consists of industrial, distribution, resource, and demand structures, although the industrial structure plays a leading role in the national economic structure (Ward et al., 2016). In the process of current economic development, the economic aggregate and the industrial structure are constantly changing and interacting. Rational adjustment of the industrial structure is not only a necessary foundation for steady economic growth, but also an inevitable requirement for sustained growth of the economic aggregate. The historical process of China's economic growth has clarified the regularity between the adjustment of the industrial structure and economic development. During the period of slow economic growth, China's total GDP and per capita GDP were both maintained at reasonably low levels. Primary industry held the highest proportion, accounting for 30%–50% of GDP, and economic growth was dependent mainly on agriculture and the traditional service industry. A large labor force was concentrated in the agricultural sector, but the agricultural infrastructure was rather weak and the situation of "weather-dependent harvesting" had not been changed, which resulted in slow economic growth. During the period of rapid economic growth, the national economy improved continuously and the scale of investment increased steadily. The dependency of economic growth on primary industry shifted to a dependency on the collaborative promotion of secondary and tertiary industries. Secondary industry accounted for about 50% of GDP, and the national economic growth depended mainly on the rapid rise of such industries, especially the manufacturing industry. The growth of capital and labor provided increasingly smaller contributions to economic growth. Conversely, the growth of the total factor productivity contributed more and more, which accelerated the pace of technological innovation, expanded the scale of investment in economic growth, and further promoted and guaranteed continuous economic growth.

Many studies have considered the relationship between economic development and energy consumption in Asian and African countries (Nasreen and Anwar, 2014; Eggoh et al., 2011), including 11 oil-exporting countries as well as 22 developed and 18 developing countries. Their findings indicate, from the perspective of the short or the long term, a two-way causality exists between energy consumption (per capita energy consumption) and economic growth (GDP per capita) in developed countries (Amri, 2017),

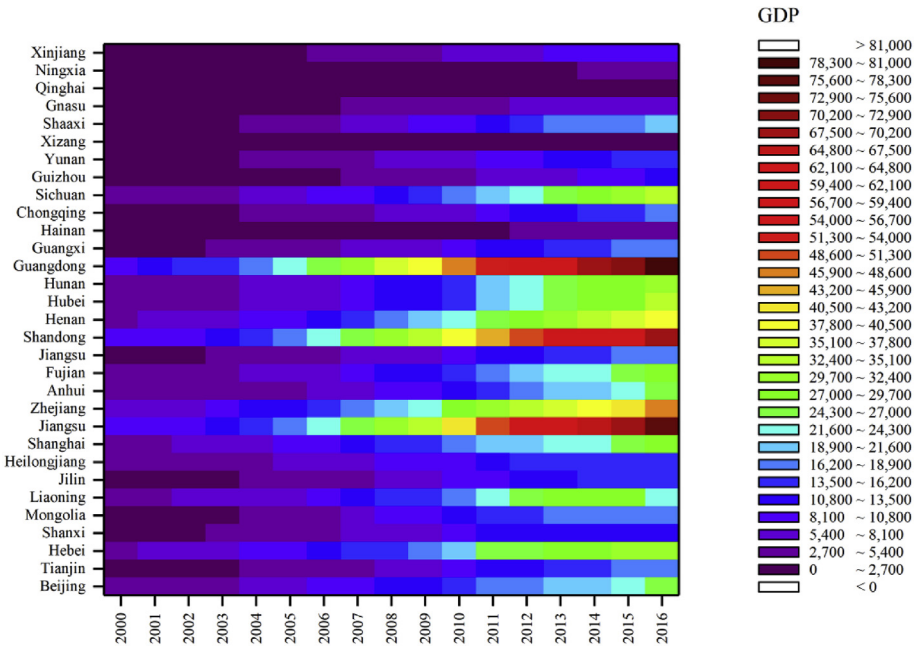


Fig. 1. Composition of the gross domestic product (GDP) of the provinces in China (2000–2016).

whereas a one-way causality exists in developing countries, where an increase of short-term energy consumption leads to economic growth (Yildirim et al., 2012). In addition, the GDP of New Zealand has been found causally related to its coal, natural gas, crude oil, electric power, and other energy sources (Ministry of Economic Development, 2011). The energy consumption of South Korea has a one-way causal relationship with its GDP, whereas a two-way causality exists between its coal consumption and economic growth. In addition to economic development, the factors of industrial structure, energy efficiency, and technological progress all have important effects on energy consumption (Sheinbaum-Pardo et al., 2012). For example, the industrial structure and recent technological changes are the main driving forces reducing energy intensity in Mexico (Sheinbaum-Pardo et al., 2012). The decline in energy consumption per unit output in the U.S.A. has been largely dependent on changes of the energy consumption structure (Muratori et al., 2013), whereas development of production technology has reduced Germany's energy consumption (Chu and Chang, 2012). Improvements in energy efficiency not only reduce energy consumption but also promote the development of industrial productivity (Kang and Lee, 2016). In addition, in some countries, population growth has led to an increase in building-related energy consumption, and the increases in both rate and amount of energy consumption by the construction industry have been far greater than other industries, including the transportation sector (Morikawa, 2012).

A model has been established to predict the energy needs of different industries in different countries (Pätäri et al., 2014). For transportation-related energy consumption, some researchers have predicted that an increase in car ownership would lead to increased demand for gasoline and other energy sources (Liddle, 2012). For example, it has been predicted that traffic-related energy consumption in India will rise sharply and that CO_2 emissions will increase from 1.98 million tons of carbon equivalent in 2000–2001 to 93.25 million tons of carbon equivalent (Srivastava et al., 2012). Furthermore, soaring private car ownership in Mexico is expected to lead to a sharp increase in gasoline demand. Moreover, the LEAP model has been used to analyze the factors influencing the energy consumption pattern and emission standard in Delhi's traffic sector and to predict the total energy demands and vehicle emissions (Azam et al., 2016). In addition, other studies have predicted overall energy demand. For example, the energy demands of the EU in 2025 (Hu et al., 2015) have been predicted under different scenarios of population and economic development by analyzing historical data from 1960 to 2000 to predict Germany's energy demands and CO_2 emissions during 2005–2030 under different energy prices (Martinsen et al., 2007). Furthermore, other research has used fuel and consumer industry models to predict Nepal's energy demand in 2030 (Gurung et al., 2013). Numerical studies have been conducted to evaluate the emissions induced by fossil fuel use in China and to identify the primary influencing factors. However, further investigation of regional differences is required. Furthermore, because of the vital importance of China's future development, consideration of various scenarios is necessary to identify the preferred route for such development according to the evolving global situation.

This study analyzed the development trends and characteristics of China's CO_2 emissions. It revealed the law for the spatiotemporal evolution of the pattern of CO_2 emissions caused by China's energy consumption in seven major regions from the perspective of different geographies and industries, and it used the logarithmic mean Divisia index (LMDI) method to analyze and deconstruct the factors influencing CO_2 emissions in those seven regions. Finally, using population, economic, and other parameters, a simulative comparison was conducted based on different scenarios, and specific measures for corresponding energy saving, emissions reduction, and climate change prevention in accordance with the laws for past, current, and future development of CO_2 emissions in China were proposed.

2. Materials and methods

The LMDI method was used to determine the primary factors influencing CO_2 emissions in China and scenario analysis was conducted to predict future fossil fuel CO_2 emissions. The main input and output parameters are outlined in the following (Fig. 2).

2.1. Decomposition of LMDI influencing factors

The factor decomposition model is one method that has been used widely in the fields of climate change and energy emission research (Stern, 2006; Gu et al., 2015). However, traditional factor decomposition methods are considered unable to meet the needs of current research because the residual terms generated in the process of such decompositions have reduced the credibility of derived research results (Li et al., 2017). Recent research has shown that the LMDI method is a complete method for decomposition analysis free of residual errors (Chong et al., 2015). Furthermore, in comparison with traditional decomposition methods, the LMDI method, which has a comparatively strict theoretical basis, has practicability, maneuverability, and is able to deal effectively with the situation of zero values. The equation for CO_2 emissions associated with energy consumption can be expressed as follows:

$$C = \sum_{ij} C_{ij} = \sum_{ij} P_i \times \frac{Q_i}{P_i} \times \frac{E_i}{Q_i} \times \frac{E_{ij}}{E_i} \times \frac{C_{ij}}{E_{ij}}, \quad (1)$$

where C indicates the CO_2 emissions caused by energy consumption, C_{ij} indicates the CO_2 emissions from j types of energy source (i.e., coal, petroleum, and natural gas) in region or province i (autonomous region or directly controlled municipality). Here, P_i indicates the population size in region or province i, Qi indicates the GDP of region or province i, Ei indicates the energy consumption of region or province i, and Eij indicates the consumption of j types of energy source in region or province i. It is assumed that the factors for economic development are $G_i = \frac{Q_i}{P_i}$, i.e., the local per capita GDP of region or province i. Energy intensity refers to the energy consumption per unit GDP. The energy structure $S_i = \frac{E_{ij}}{E_i}$ refers to the proportion of the consumption of j types of energy source in region or province i in relation to the total energy consumption of the region or province. The energy CO_2 emission coefficient $U_i = \frac{C_{ij}}{E_{ij}}$ refers to the CO_2 emissions from j types of energy source in the i-th region or province:

$$C_i = \sum_{ij} C_{ij} = \sum_{ij} P_i G_i I_i S_i U_{ij}. \quad (2)$$

The change in CO_2 emissions during period T, relative to the base period, can be expressed as a difference or as a ratio:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_P + \Delta C_G + \Delta C_I + \Delta C_S + \Delta C_U + \Delta C_{rsd}, \quad (3)$$

$$Dtot = \frac{C^T}{C^0} = D_P D_G D_I D_S D_U D_{rsd}, \quad (4)$$

where ΔC_P, ΔC_G, ΔC_I, ΔC_S, and ΔC_U indicate the decompositions of the CO_2 emissions changes against population development, economic development, energy intensity, energy structure, and the energy CO_2 emission coefficient, respectively, in region or province i. and ΔC_{rsd} is the residual term. In Eq. (4), D_P, D_G, D_I, D_S, and D_U

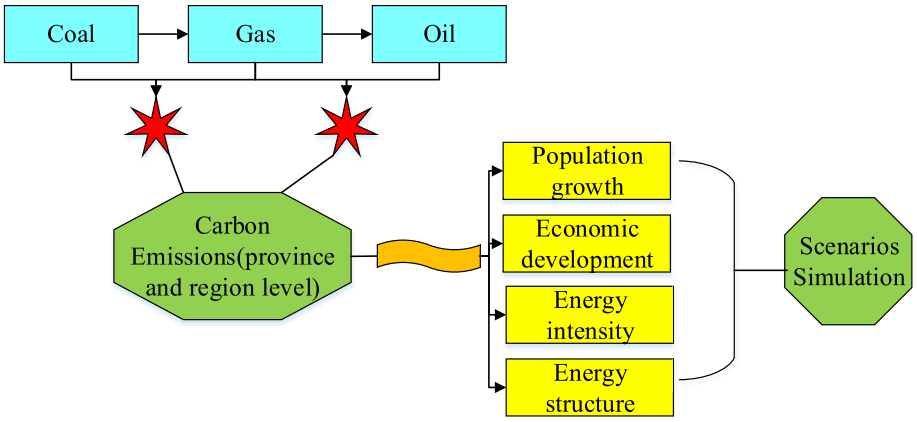


Fig. 2. Flowchart of the total input and output pathways.

represent the decompositions of different factors against CO_2 emissions, and D_{rsd} indicates the residual term. Research has shown that the difference method can express intuitively the changes of CO_2 emissions during a research period. The decomposition results of all the factors are as follows:

$$\Delta C_G = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{LnC_{ij}^T - LnC_{ij}^0} Ln\left(\frac{G_i^T}{G_i^0}\right), \quad (5)$$

$$\Delta C_P = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{LnC_{ij}^T - LnC_{ij}^0} Ln\left(\frac{P_i^T}{P_i^0}\right), \quad (6)$$

$$\Delta C_S = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{LnC_{ij}^T - LnC_{ij}^0} Ln\left(\frac{S_{ij}^T}{S_{ij}^0}\right), \quad (7)$$

$$\Delta C_I = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{LnC_{ij}^T - LnC_{ij}^0} Ln\left(\frac{I_i^T}{I_i^0}\right). \quad (8)$$

2.2. Scenario settings

Future economic development is full of great uncertainty, as is the development of energy consumption. Future energy consumption and its corresponding CO_2 emissions can be predicted based on the rules and states of past and present development (Bai, 2017). In this analysis, future scenarios were predicted by integrating qualitative and quantitative analysis methods and related modeling tools were adopted to predict China's CO_2 emissions in 2020–2030. In all, six scenarios were included in this study (listed below), which were compared against corresponding Shared Socioeconomic Pathways.

Go with the Flow develops according to current policies and systems. It provides a scenario for development in accordance with the economic growth rate, population development scale, urbanization, and industrialization process, adopting the status quo regarding recent energy consumption and energy demands if consistent with current socioeconomic and environmental policies.

Nature@work achieves development by constructing a multifunctional landscape that places the main emphasis on ecosystem protection. In this scenario, sustainability is the fundamental principle for the development of all social sectors. Under this scenario, the intensity of energy consumption and CO_2 emissions both show reasonably low levels, featuring slow economic development, high urbanization and industrialization, and stable population growth.

Green and Pleasant Land focuses on protecting the ecosystem with future economic growth concentrated on secondary and tertiary industries, while the primary industry (i.e., agriculture) maintains a downward trend. Rural development is subject to reasonably little pressure and its space is used to beautify the countryside and to play a positive role in biodiversity protection. Under this scenario, science and technology (e.g., biotechnology) progress slowly, while development in other areas such as social networks and green technology increases. This scenario boasts a high sense of management and protection of the environment. Moreover, the energy and CO_2 emissions are maintained at low levels of intensity, the population growth is stable, and a high level of economic development is maintained.

World Markets eliminates trade barriers, makes full use of international market development, and emphasizes economic growth and trade freedom. Although trade barriers disappear and imports increase, no emphasis is placed on environmental protection. Under this scenario, population growth is stable, and although the factor of an aging population is reasonably serious, economic growth is strong. However, there are occasional global market crises and periodic stagnation, and it is weak in environmental awareness during periods of economic development.

National Security tries to reduce the impact of international markets and to improve the efficiency of utilization. Many of its characteristics are similar to the World Markets scenario, but under this scenario, because of the continuous shortage of global resources, the state pays great attention to the development of its core technology and industry, as well as to national self-sufficiency and economic protection. Therefore, the government protects its own economy by intervening in the free market, setting up trade barriers, and enforcing other protection policies. Under this scenario, population growth is stable and economic development is maintained at a high level.

Local Stewardship makes use of local resources and environmental conditions as much as possible. A slow pace of life is proposed, which aims to move toward a society of low intensity and low resource consumption. The values under this scenario are considerably different compared with current values and attitudes. This scenario is characterized by slow population growth, strictly limited immigration, an ever-growing elderly population, stable economy, reasonable health improvement, massive satisfaction of most needs, rare commodity supply surplus, low economic development, and low intensity in energy consumption and CO_2

emissions.

3. Results and analysis

3.1. Primary energy use and CO_2 emission status

According to the annual quantity of CO_2 emissions associated with primary energy consumption, the 30 provinces (autonomous regions and municipalities) of China were divided into 4 levels. Level 1 means slight emissions (CO_2 emissions of <30 million tons), level 2 means moderate emissions (CO_2 emissions of 30–80 million tons), level 3 means severe emissions (CO_2 emissions of 80–200 million tons), and level 4 means extremely severe emissions (CO_2 emissions of >200 million tons). In 2005 (Fig. 3a), Shandong, Shanxi, and Hebei suffered extremely severe emissions, Henan, Jiangsu, Inner Mongolia, and Liaoning suffered severe emissions, while the provinces, municipalities, and autonomous regions suffered light and severe emissions. However, by 2010 (Fig. 3b), Shandong's annual CO_2 emissions were nearly 400 million tons, while those of other provinces such as Shanxi and Hebei were nearly 300 million tons. Moreover, by 2015 (Fig. 3c), Shandong's annual CO_2 emissions exceeded 400 million tons, those of Shanxi and Inner Mongolia were nearly 400 million tons, and the CO_2 emissions of Jiangsu and Henan were above 200 million tons.

During 2005–2015, CO_2 emissions in China attributable to coal showed a trend of year-on-year increase from 3.59 billion tons of carbon in 2005 to 5.31 billion tons in 2014, i.e., growth by a factor of 1.47 times in a decade. As the main source of CO_2 emissions, the emissions from coal accounted for 50%–60% of the national total; however, this fraction showed a trend of year-on-year decrease from 55.15% in 2005 to 50.00% in 2015, closely related to the national macroeconomic policy. During 2005–2015, the CO_2 emissions in China from oil showed a trend of year-on-year increase from 1.41 billion tons of carbon in 2005 to 2.24 billion tons in 2015. As one of the three pillars of China's energy and as the second largest source of CO_2 emissions, emissions attributable to oil remained largely flat, accounting for 20%–21% of the national total.

Similar to the worldwide trend of development, China's energy is experiencing the development process of “oil followed by gas”. Over the previous few decades, CO_2 emissions in China attributable to consumption of natural gas rose from 135.59 million tons of carbon in 2005 to 519.32 million tons in 2015 (i.e., an increase of 3.83 times), and the overall proportion of the national total rose from 2.1% in 2005 to 4.9% in 2015.

3.2. Emissions of CO_2 in different regions

As one of the major producers and consumers of coal in the world, China's coal consumption, which has had a pivotal role in the nation's regional development, has resulted in considerable quantities of CO_2 emissions.

During 2005–2015, CO_2 emissions attributable to coal consumption (Fig. 4a) in the seven major regions of China showed a trend of increase. In these seven major regions, CO_2 emissions rose reasonably quickly before 2010, but at a relatively slower rate over the following five years. By 2015, CO_2 emissions from coal in North China, East China, and Central China had reached 584.61, 635.68, and 251.79 million tons of carbon, respectively, accounting for 63.6% of China's total emissions.

The CO_2 emissions attributable to oil consumption (Fig. 4b) in China's seven major regions before 2012 changed reasonably slowly, except in the East China region. However, during 2012–2013, emissions decreased markedly in Northeast and Northwest China but showed gradual year-on-year increases in other regions. After 2013, emissions increased slowly in all years.

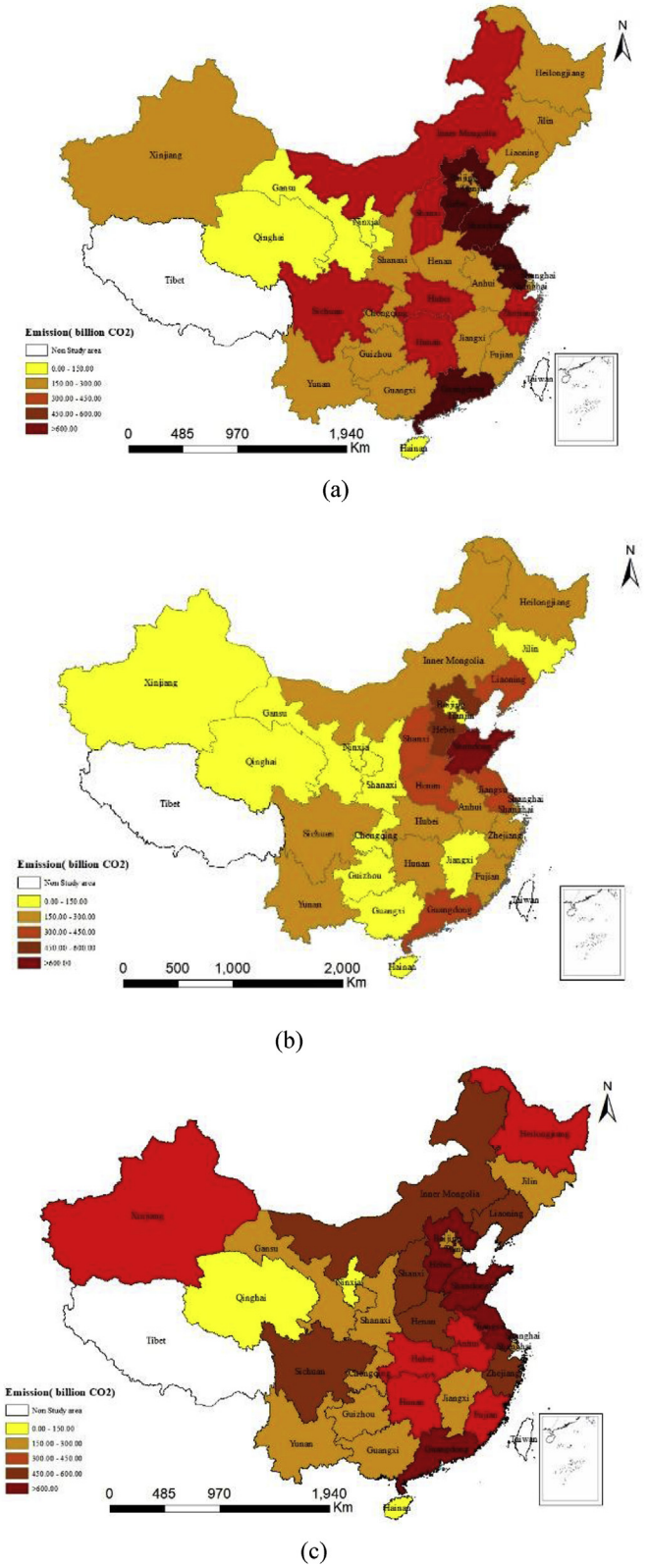
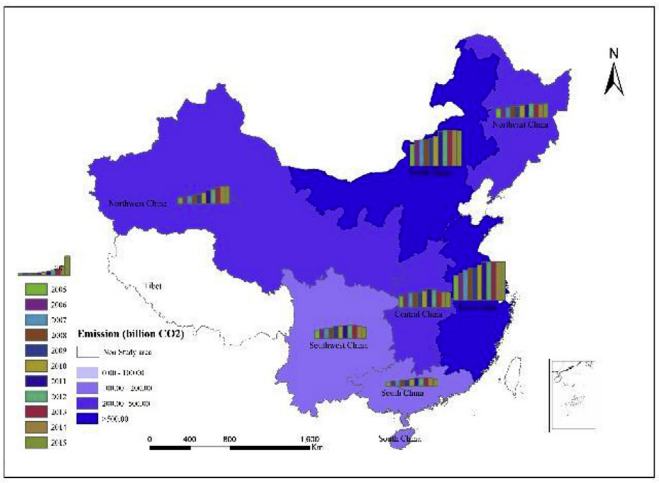
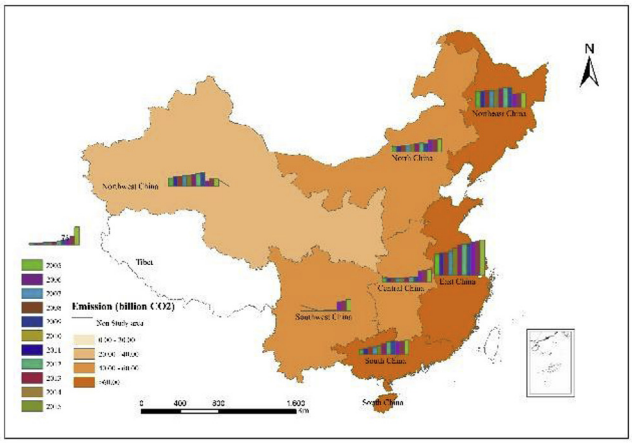


Fig. 3. Annual CO_2 emissions from China's primary energy sources: (a) 2005, (b) 2010, and (c) 2015.

The emissions developed more consistently in these major regions, but because of varying levels of economic development and energy consumption, considerable differences existed in the levels of CO_2



(a)



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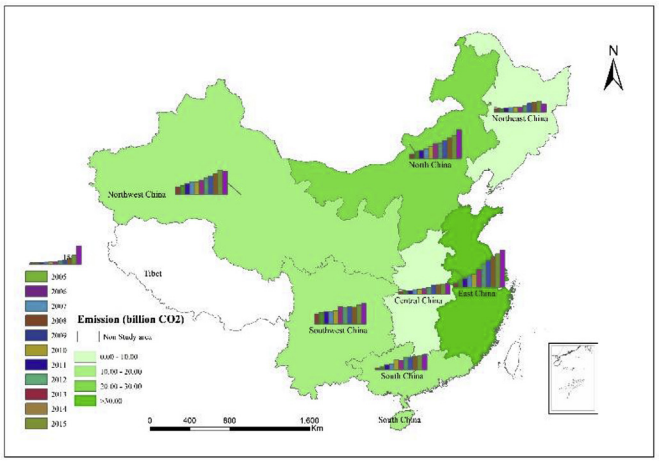

(c)

Fig. 4. Distribution of regional CO_2 emissions in China: (a) coal, (b) gas, and (c) oil.

emissions caused by oil consumption. For example, East China consumed the largest amount of oil every year; thus, its CO_2 emissions ranked first in China, i.e., up to 151.28 million tons of carbon in 2015, which accounted for 32.6% of the total emissions. Northeast China was second highest with CO_2 emissions of up to 62.3 million tons of carbon accounting for 13.4% of the total. Northwest China consumed the lowest amount of oil; its CO_2 emissions were only 32.57 million tons of carbon in 2015, which accounted for 7.02% of the total.

Affected by resource storage conditions, the Southwest and Northwest regions of China constitute two major areas of production and consumption of natural gas. However, under the influence of west–east gas transmission, the consumption of natural gas in East China has been increasing gradually (Fig. 4c). After 2009, the quantities of CO_2 emissions in East China and North China surpassed the Southwest region. Moreover, by 2005, East China had the highest level of emissions, i.e., up to 30 million tons of carbon, which accounted for 0.25% of the total emissions. In the Northwest region, CO_2 emissions attributable to natural gas increased up to 1.9 million tons of carbon by 2015. Conversely, in the Northeast region, although CO_2 emissions initially increased slowly, they declined to 50,000 tons of carbon during 2014–2015.

According to regional emission levels and energy consumption structures, the areas of North China, Southwest China, and Southern China were selected to represent severe, moderate, and mild carbon emission areas, respectively, corresponding to areas of consumption of mainly coal, natural gas, and oil, respectively (Table 1). In 2000–2005, the total emissions of the three regions increased, although the increase during 2005–2015 was significantly lower than in 2000–2005.

Coal accounted for the largest proportion of energy consumption in North China, and the associated CO_2 emissions accounted for 89%–92% of the regional total, followed by emissions associated with oil (8%–10%) and natural gas consumption. Although the emissions associated with natural gas increased continuously, they accounted for only 0.2% of the total in 2014.

Southwest China is the largest producer and consumer of natural gas in China. Its CO_2 emissions attributable to natural gas accounted for 5%–7% in 2000–2005, i.e., much higher than those of North China and South China during the same period. In addition, CO_2 emissions attributable to coal, as the main source of energy within this area, accounted for >85% of the regional total.

The region of South China is the second largest consumer of oil in China, and its CO_2 emissions attributable to oil accounted for about 40% of the regional total. However, its emissions from coal consumption accounted for about 60%, far lower than from the same energy source in North China and Southwest China, which is also one of the main reasons why this region is a mild carbon emission area.

Coal is the most important source of CO_2 emissions in North China, Southwest China, and South China. Emissions attributable to coal consumption in these regions accounted for about 70%–92% of the total, followed by oil (5%–30%) and natural gas (0.1%–6.8%). During 2000–2015, although the dominance of coal in the energy structure of North China, Southwest China, and South China did not change much, the energy structure in each region was constantly optimized and moving toward the road of “low emission and low pollution” in relation to energy consumption.

3.3. Analysis of factors influencing CO_2 in different regions

From 2005 to 2015, the CO_2 emissions caused by energy consumption in the various regions of China had different degrees of growth (Table 2). The largest growth rate occurred in East China (i.e., up to 15.83 billion tons), followed by North China (up to 1.16 billion tons), and Central China (up to 1.04393 billion tons). The other four regions of China maintained growth of 50–66 million tons with Southwest China, South China, North China, and West China ranked first, second, third, and fourth, respectively, according to growth rate. During 2005–2015, population growth and economic development drove CO_2 emissions in China, with

Table 1
Emissions of CO_2 and corresponding energy compositions in three typical regions of China in 2000, 2005, and 2015.

Areas	Emission (10,000 tons of carbon)	2000			2005			2015		
		coal	oil	gas	coal	Oil	Gas	coal	oil	gas
		174.32	19.55	1.47	323.07	32.4	3.45	596.33	52.59	1.84
North China	Percentage (%)	89.2	10	0.8	90	9	1	92	8	2.8
Southwest China	Emission (10,000 tons of carbon)	73.39	6.86	5.89	127.56	13.7	7.88	210.2	43.24	15.65
	Percentage (%)	85.2	8	6.8	85.5	9.2	5.3	82	16	5.8
South China	Emission (10,000 tons of carbon)	38.65	26.02	0.38	67.72	47.64	1.42	134.04	57.24	11.21
	Percentage (%)	59.4	40	0.6	58	40.8	1.2	70	28	5.5

Table 2
Effects of different factors on China's CO_2 emissions.

Year	CO_2 Emissions	Population growth	Economic development	Energy intensity	Energy structure
2005–2010	868.48	50.81	1172.47	−258.92	−95.88
2010–2015	915.30	100.38	1857.30	−1005.94	−36.44
2005–2015	1619.85	157.17	2425.23	−1082.76	−144.00

Note: In the table, the value in the column "CO_2 Emissions" refers to the sum of the "Population growth, Economic development, Energy intensity, and Energy structure." A positive value indicates the factor has promoted CO_2 emissions, whereas a negative value indicates an inhibitory effect (the same applies to values in other tables).

contribution rates of up to 4.15% and 95.85%, respectively, i.e., the contribution from population development was far less than from economic development. The reduction of energy intensity and the optimization of the energy structure both slowed the rate of CO_2 emissions somewhat, with contribution rates of up to 87.7% and 12.3%, respectively, i.e., the contribution from energy intensity was far greater than from the energy structure.

Population development has promoted the growth of CO_2 emissions in China, although the effect has not been very significant with rates of 4.15%, 10.9%, and 4.5% for its contribution to the growth of CO_2 emissions in 2005–2010, 2010–2015, and 2005–2015, respectively (Fig. 5). During the study period, population development in East China has promoted the greatest increase of CO_2 emissions (by 48.58 million tons). Conversely, in Southwest China, population development has reduced CO_2 emissions by 2.32 million tons. Thus, the impact of population growth on the promotion of CO_2 emissions has tended to become weaker.

Economic development (Fig. 5) has been the most important factor driving the growth of CO_2 emissions in China, contributing 95.85%, 91.00%, and 95.50% to the growth of CO_2 emissions in 2005–2010, 2010–2015, and 2005–2015, respectively. During the study period, economic development has promoted the greatest increase of CO_2 emissions (by 649.8 million tons) in North China, whereas the least marked increase has been in South China (156.25 million tons). The economy has developed rapidly in all regions, which has accelerated the rate of growth of CO_2 emissions.

Energy intensity is the most important influencing factor regarding the mitigation of CO_2 emissions in China. The rate of its contribution to the reduction of CO_2 emissions in 2005–2010, 2010–2015, and 2005–2015 was 72.99%, 96.50%, and 87.67%, respectively. During the study period, the reduction of energy intensity has produced the greatest reduction of CO_2 emissions (by 256.41 million tons) in North China, whereas the least marked decrease has been in South China (only 40,000 tons).

If its energy structure could be optimized, then China's CO_2 emissions could be reduced. The rate of the contribution of energy structure to the reduction of CO_2 emissions in 2005–2010, 2010–2015, and 2005–2015 was 18.01%, 3.50%, and 12.33%, respectively. During the study period, optimization of the energy structure has produced the greatest reduction in CO_2 emissions (by 264.50 million tons) in North China, whereas the least marked decrease has been in Northwest China (only 34.75 million tons).

3.4. Prospects under different scenarios

According to the steps outlined above, we predicted future CO_2 emissions under six different scenarios.

China's CO_2 emissions will continue to grow during 2015–2030,

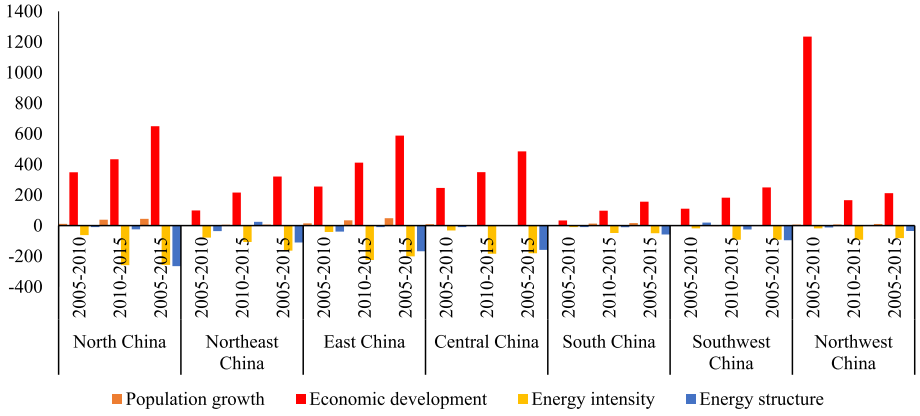

Fig. 5. Impacts of different factors on regional CO_2 emissions.

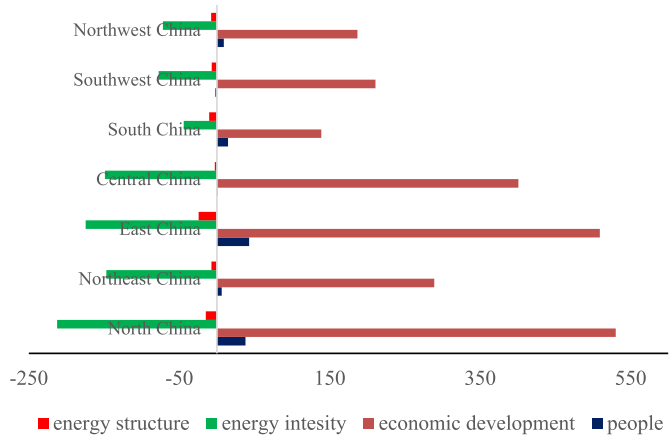

Fig. 6. Factors influencing CO_2 emissions in China.

increasing by a factor of 0.8–2.2 times. Under the Local Stewardship and World Markets scenarios, the CO_2 emissions attributable to coal and oil consumption will increase, whereas they will reduce under the other scenarios. Moreover, in all scenarios, CO_2 emissions from natural gas consumption will increase.

Under the Local Stewardship, Green and Pleasant Land, Nature@Work, World Markets, National Security, and Go with the Flow scenarios (Fig. 6), the national CO_2 emissions by 2030 will reach 2.21, 11.81, 10.59, 24.32, 14.64, and 9.5 billion tons of carbon, respectively. Under the Go with the Flow and World Markets scenarios, the CO_2 emissions attributable to coal and oil consumption will increase, whereas they will decrease under the other scenarios. In all scenarios, CO_2 emissions from natural gas consumption will increase (see Fig. 7).

4. Conclusions and discussion

Energy consumption and CO_2 emissions have long been important areas of research in political, economic, and diplomatic fields in China and internationally. Focusing on the issue of energy consumption and associated CO_2 emissions, this study analyzed the basic scenario of global energy consumption and related CO_2 emissions, as well as the developmental history of China's economy, energy, and CO_2 emissions. The investigation revealed the underlying characteristics and laws of CO_2 emissions in relation to regional energy consumption in China, analyzed the factors influencing CO_2 emissions using the LMDI method, and simulated

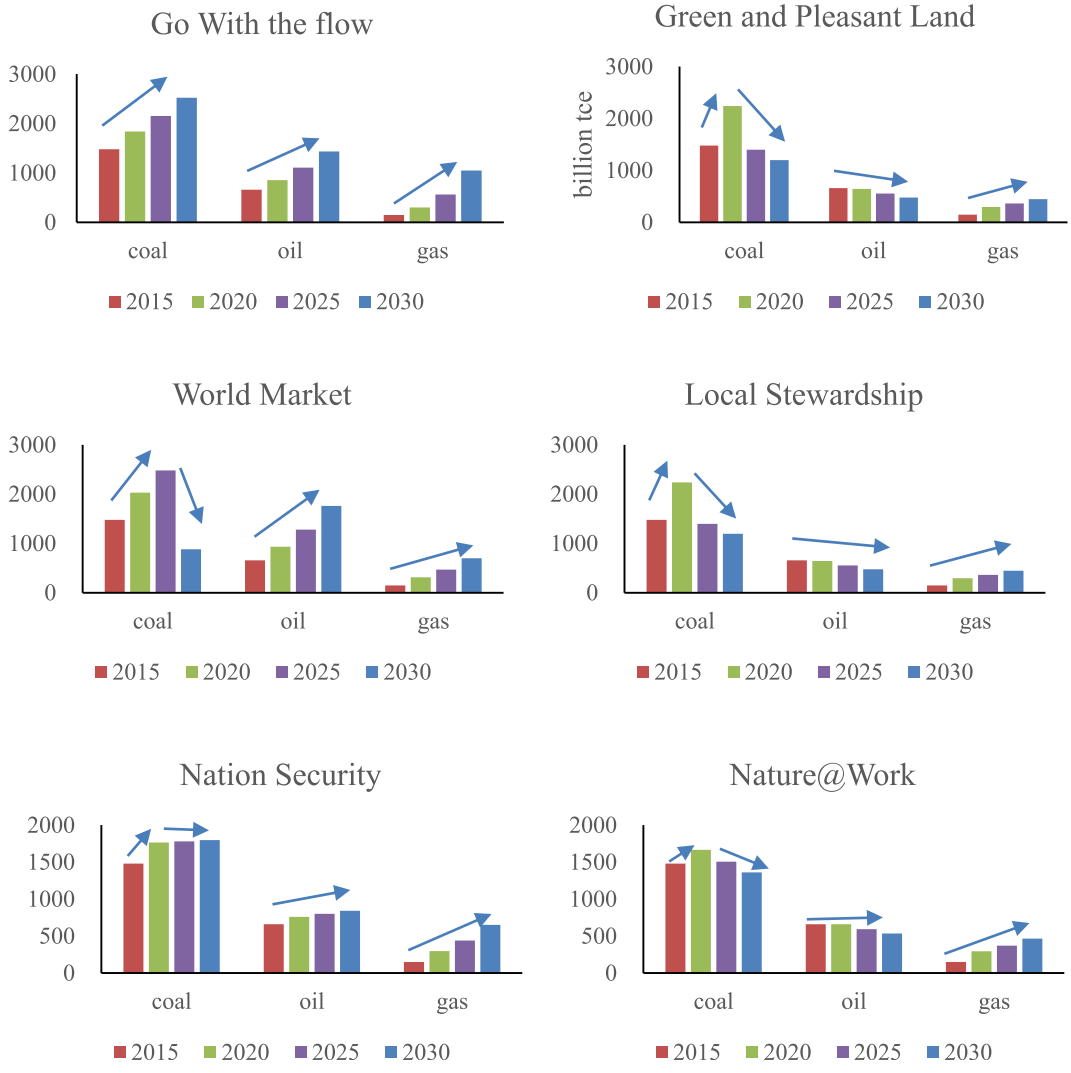

Fig. 7. Predicted energy consumption of China under six scenarios (2015–2030).

China's future CO_2 emissions (2015–2030) under six different scenarios. As a developing power, it was found that China has maintained steady economic growth, produced an adequate energy supply, but generated overall increases of CO_2 emissions, although the per capita emissions have been very low. Specifically, China's economic development experienced slow growth during 1952–1977 and rapid growth during 1978–2015, and its energy production and consumption both increased substantially during the latter period.

The reduction of CO_2 emissions in China will require coordinated regional development relations, improved energy efficiency, optimized energy consumption structures, the development of low-carbon and renewable energy resources, and other relevant measures. Moreover, in response to the national priority, energy conservation and emissions reduction should be elevated in importance, research on energy saving, emissions reduction, and energy efficiency improvements should be increased, and energy-saving technologies should be evaluated and promoted to exploit their full potential in relation to the reduction of CO_2 emissions. It is recommended this work be addressed using a two-pronged approach. First, from the perspective of regional characteristics, systematic and scientific measures for energy saving and emissions reduction should be implemented in North China, East China, Central China, and other regions with substantial CO_2 emissions. In particular, provinces (autonomous regions and municipalities) characterized by high energy intensity and considerable potential for reduced energy consumption (e.g., Shanxi, Hebei, Liaoning, and others), should undertake appropriate energy saving and consumption reduction measures to reduce their energy consumption and to lower their CO_2 emissions. Second, it will be necessary to reduce the energy intensity of the industrial, transportation, and commercial sectors, especially those industries with high consumption of energy, e.g., electric power generation, oil refining, and building material production. Given China's energy resources and consumption status, appropriate reduction of the proportion of coal consumption relative to the level associated with the current economic development will be highly important in reducing CO_2 emissions, as will the increased use of oil and natural gas. Furthermore, optimization of the energy structure in industries such as steel and building material production and electric power generation, as well as in coal-consuming provinces such as Shanxi, Hebei, Yunnan, and Guizhou, will play an important role in reducing overall CO_2 emissions.

Guided by the LMDI method and scenarios analysis, this study calculated the CO_2 emissions induced by fossil fuel consumption in different provinces and regions of China. Using economic data from 30 provinces in China, we concluded economic development has been the main factor that has led to increased CO_2 emission, which is a finding that will provide insight for policy makers. However, this study focused only on current CO_2 emissions and their future development, whereas the investigation of carbon emission intensity will be an interesting topic in future studies. With regard to the scenario analysis, we produced a set of indicators to simulate future development and further investigation of these indicators will be worthwhile.

Acknowledgement

This research was Supported by the National Key Research and Development Program of China (Grant No. 2016YFA0602500).

Appendix I. Parameter Setting for each scenario

parameter	Scenarios	2015	2020	2025	2030
Population growth (100 million)	Go with the Flow	13.75	14.20	14.35	14.50
	Nature@work	13.75	14.15	14.25	14.41
	Green and Pleasant Land	13.75	14.10	14.17	14.29
	World Market	13.75	14.27	14.45	14.45
	National Security	13.75	14.17	14.29	14.51
	Local Stewardship	13.75	14.10	14.17	14.31
per capital GDP(Yuan)	Go with the Flow	42,901.98	59,611.98	72,179.07	87,395.49
	Nature@work	42,901.98	59,611.98	85,979.50	124,009.88
	Green and Pleasant Land	42,901.98	59,611.98	76,081.67	97,101.64
	World Market	42,901.98	59,611.98	76,081.67	97,101.64
	National Security	42,901.98	54,259.74	62,901.91	72,920.55
	Local Stewardship	42,901.98	49,343.94	54,479.70	60,149.99
Energy intensity (tons of standard coal/10 thousand yuan)	Go with the Flow	0.59	0.50	0.45	0.39
	Nature@work	0.59	0.48	0.43	0.37
	Green and Pleasant Land	0.59	0.46	0.44	0.35
	World Market	0.59	0.56	0.49	0.45
	National Security	0.59	0.54	0.47	0.43
	Local Stewardship	0.59	0.52	0.46	0.41
carbon dioxide emissions intensity (ton/10 thousand yuan)	Go with the Flow	1.86	1.69	1.14	0.77
	Nature@work	1.86	1.68	1.12	0.74
	Green and Pleasant Land	1.86	1.65	1.08	0.71
	World Market	1.86	1.70	1.21	0.86
	National Security	1.86	1.69	1.18	0.83
	Local Stewardship	1.86	1.69	1.16	0.80

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